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BLOWHOLES, POROSITY, AND UNSOUNDNESS IN ALUMINUM-ALLOY CASTINGS

BY

ROBERT J. ANDERSON

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BLOWHOLES, POROSITY, AND UNSOUNDNESS IN ALUMINUM-ALLOY CASTINGS.

By Robert J. Anderson.

INTRODUCTION.

From an insignficant beginning some 20 years ago the aluminum-alloy casting industry, in magnitude, has become one of the more important branches of nonferrous metallurgy. The technology of aluminum-alloy casting, however, has not developed to a high plane as yet because of the infancy of the industry and more largely because of adherence to traditions and precedents. There is a large amount of research, both pure and applied, still to be undertaken. Investigations in the metallurgy of aluminum are of prime importance because of the present paucity of accurate data; as a matter of fact, it is doubtful whether any industry in the metallurgical field is so empirical in practice as the aluminum industry. This statement is admittedly very general, but is sufficiently clear to give an idea of the existing status of conditions. The empiricism mentioned is true of aluminum-foundry practice, but it is even more marked in aluminum-die casting and rolling-mill practice. The installation of testing laboratories and the acquisition of technical staffs, in isolated instances, has greatly aided in putting metallurgical matters on a more rational basis; nevertheless, probably not one-tenth as much research, either pure or applied, has been carried out for aluminum as for iron and steel. The national importance of the aluminum industry urgently requires investigations for the purpose of improving the quality of the products, preventing waste, and instituting improved methods of practice. In an endeavor to aid in this direction the Bureau of Mines has undertaken a number of investigations. Inquiry in the industry has largely corroborated the above statements, and it is hoped that the results of the researches undertaken will prove useful.

In aluminum-alloy casting practice one of the most serious problems is the prevention in castings of defects that lead to rejection and consequent scrappage. Under the general subject of defects, one particular class of defects—namely, blowholes, porosity, and unsoundness—is very serious. From the standpoint of the foundry-

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man, the occurrence of these defects is exasperating, because at times blowholes appear and disappear in a seemingly mysterious manner without the reasons for either condition being known. It is obvious, however, that it might be considered possible to ascertain the causes of defectiveness and, when these are found, to apply methods of prevention. To attempt to remedy troubles the causes of which are unknown is useless.

In connection with its research work on the metallurgy of aluminum, the Bureau of Mines, through its mining experiment station at Pittsburgh, Pa., undertook a study of the problem relating to blowholes, porosity, and unsoundness in aluminum-alloy castings. The difficulties involved in such an undertaking will be readily apparent to the experienced foundryman, because there are so many variables to be dealt with. The object of the investigation was threefold—to ascertain the causes that produce the defects mentioned, to correlate all available information, and to suggest methods of prevention. The results of this study are presented in this report; they can at best be regarded as preliminary, because actual foundry results can only be measured from viewing working conditions over an extended period of time. However, it is deemed advisable to place the available information before the industry now.

MAGNITUDE OF THE LIGHT-ALLOY INDUSTRY.

According to a survey made by "The Foundry"[a] in 1918, there were 2,037 foundries melting aluminum in the United States in that year. These are not exclusively aluminum-alloy foundries; indeed, with the possible exception of plants casting aluminum cooking utensils, there are few foundries in the United States that make aluminum wares only. Many brass foundries produce aluminum-alloy castings, and gray-iron shops also operate aluminum departments. Aluminum die-casting manufacturers also cast other nonferrous products. To obtain reliable data on the production of alumium-alloy castings as such is an extremely difficult matter, because of the scattered conditions in the industry, the large number of small foundries operating with only one or two molders, and the uncertainty as to the use of secondary and remelt aluminum. The Bureau of Mines, however, hopes at some future date to gather reliable data in this connection.

The average amount of aluminum scrap made in sand-casting practice may be conservatively put at about 12 per cent of the metal melted, but the figure varies exceedingly with the class of castings, the individual foundry, the kind of alloy, and other factors.

[a] Anon., Foundry industry makes big gain in two years: The Foundry, vol. 46, October, 1918, pp. 455–460.

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In certain instances which have come to the attention of the writer, some foundries have turned out practically nothing but scrap until they were financially unable to carry the burden any longer. As regards simple castings which do not have to meet any specifications to speak of, the proportion of scrap may be as low as 1 per cent and under. Aircraft and motor-car castings which may be complicated and difficult to make, and which in addition must conform to exacting specifications, may consistently result in scrap to the extent of 25 per cent or more. Foundry defectives can be due to many causes, and the total percentage of scrap may be raised on machining when so-called machine-shop scrap is rejected. Any exact figures as to scrap production for the country can not be regarded now as much better than guesses, because of the variable conditions in an unstandardized industry. The figures in one foundry for a motor crank case would be totally inapplicable to another foundry using different methods of molding and melting. Figures of this sort can be obtained only after a long time but would no doubt be of immense value to the light-alloy industry.

The discussion in this report is confined in the main to blowholes, porosity, and unsoundness, but there are, of course, many other defects which arise in aluminum-alloy castings and which are properly regarded as cause for rejection under specifications, if indeed they do not totally ruin the casting for any use. In addition to blowholes and unsoundness, the practical foundryman is confronted with warping and shrinkage, cracks, misruns, sand holes, chill blows and core blows, poor venting and ramming, and a number of other factors resulting in defectives. The number of variables possible in foundry work is almost limitless, and this fact, of course, beclouds the study of the problem in its entirety. Consequently, it is extremely hazardous to generalize broadly on the results of tests unless the number of variables are well in hand and their influences carefully considered.

The present report does not deal with the many possible variables, except in so far as a recognition of their existence and influences is necessary in the study of unsoundness. In discussing the subject, the practical foundryman wants to know (1) what causes blowholes, porosity, and unsoundness, and (2) how these defects can be prevented. The answers to these questions, together with the accumulated data which lead to a tentative solution of the problem, are set forth in the following pages.

UNSOUNDNESS IN GENERAL AND THE FACTORS AFFECTING IT.

The urgent demand for a systematic research on the general subject of blowholes, porosity, and unsoundness in aluminum-alloy castings has already been shown. Before taking up an account of the experi-

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mental work performed in the present investigation, it is deemed advisable to discuss some of the factors that may influence the occurrence of the defects. A review of the literature is also included for those interested. It is a somewhat lamentable fact that such a sharp line has been drawn between ferrous and nonferrous alloys; there is little doubt that the methods which have been so rigorously applied in investigations of steel would have been equally successful for aluminum, bearing in mind, of course, the limitations imposed by the latter. Accordingly, it will also be well to have in mind the main facts as to the occurrence of blowholes and porosity in steel when making inquiry into similar defects in aluminum-alloy castings. Blowholes in steel have been adequately discussed by a number of writers. Before entering into a discussion of the various factors affecting the soundness of castings, it will be well to first define the terms blowholes, porosity, and unsoundness, so that what is meant will be clearly understood at the outset.

DEFINITION OF BLOWHOLES, POROSITY, AND UNSOUNDNESS.

Blowholes are regarded as voids within a frozen alloy, filled with air or other entrapped gas, and the entrapped gas is held to be the cause of the blowholes. Blowholes may vary considerably in size, but in aluminum-alloy castings exceedingly large holes are not often found. Small holes, say 0.025 to 0.075 inch in diameter, and pinholes, or microscopic holes, are the rule, rather than otherwise. For example, Plate I, *A*, shows a macrograph of a miscrosection cut from an unsound casting of No. 12 alloy; the entire casting was full of holes.

Porosity is held to be the inability of a casting to withstand pressure, or a casting is said to be porous when it shows seepage under the open test with methylene-blue and gasoline. Porosity may be due to blowholes, cracks, or occluded foreign matter, or any two of these, or all three. In foundry practice, a casting with small macroscopic pinholes is held to be porous, and while this may often be the case, surface sand holes are at times confused with deep-seated blowholes, and the former would have nothing to do with porosity. Plate I, *B*, shows a macrograph of a section cut from a casting showing porosity as indicated by the open gasoline test; the alloy was approximately No. 12 in composition.

Unsoundness is doubtless an undesirable term because of its vagueness; it is used indiscriminately to include blowholes and porosity, and to describe conditions where there may be much foreign nonmetallic occluded matter present, and the like. With these ideas in mind, inquiry will now be made into the cause for such defects.

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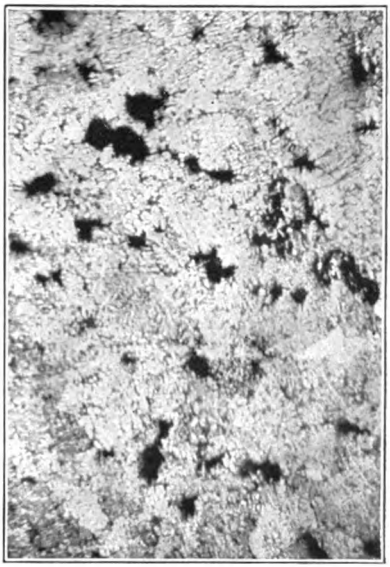
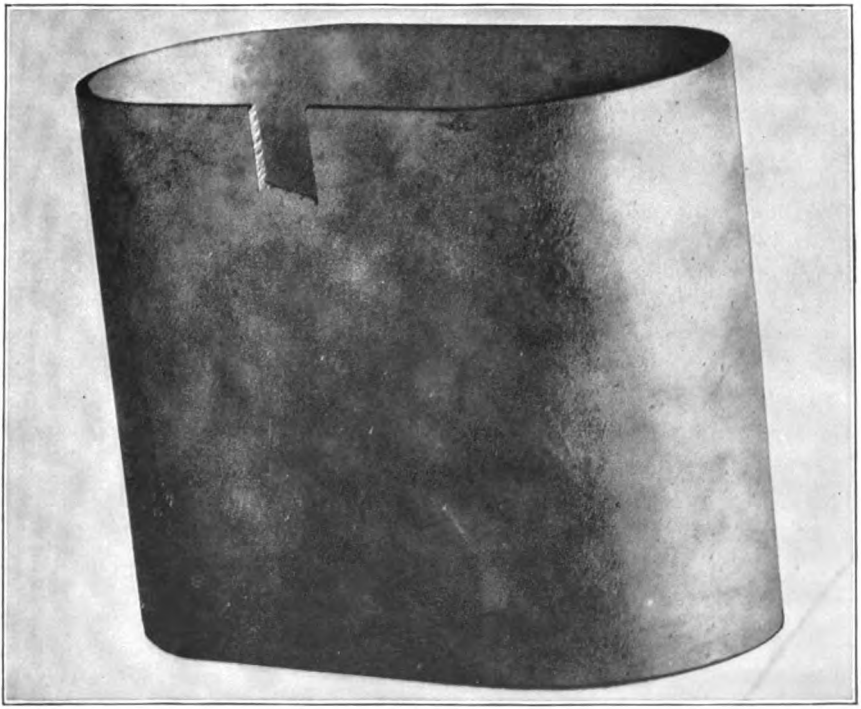
A. BLOWHOLES IN 92:8 ALUMINUM-COPPER ALLOY; UNETCHED. (X 5)



B. POROSITY IN 92:8 ALUMINUM-COPPER ALLOY, SHOWING SEEPAGE IN THE OPEN GASOLINE TEST; ETCHED WITH NaOH. (X 7)



C. FORM OF THIN SHELLS POURED IN THE CASTING EXPERIMENTS (X 0.5)

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GENERAL FACTORS AFFECTING THE SOUNDNESS OF CASTINGS.

The experience of die-casting manufacture has thrown some light on the problem of blowholes; in the die-casting process the matter of entrapped air is of serious importance. Pack[a] and others have been able to produce blowholes at will in die castings, but the production of die castings free from blowholes has been one of the most serious problems in the die-casting industry. Blowholes are the result of entrapped air or gas and should be sharply distinguished from shrinkage holes, which are the result of contraction of volume. A frozen metal[b] or alloy in the form of a casting often contains holes of various sizes or is porous; these defects are primarily caused by the liberation of gases on freezing, and the contraction or shrinkage of the metal. The liberation of gas on freezing may be minimized by keeping the temperature of the metal low, but some gas is always set free. As to contraction of volume on freezing, there is no known method of controlling, to amount to anything, the contraction in a given alloy, although the amount of contraction can be modified within limits by the addition of additive elements. Control of shrinkage for steel ingots is effected by the use of hot tops, which provide a means of feeding the top of the ingot and thus confining the pipe and blowholes within a relatively restricted volume. In castings, as such, it is at times possible to use large gates for the purpose of feeding small, thin sections and thereby minimizing the effects of contraction. In a casting, porosity, blowholes, and unsoundness are due to a number of factors, operating singly or in combination. The most important of these are the following:

(1) Overheating the melt, leading to change in composition by oxidation, volatilization, or interaction with the melting pot, and undue absorption of gases with resultant liberation on freezing.

(2) High casting temperature, causing abnormally slow cooling in the mold, coarse microstructure, liability to segregation, and some of the difficulties in (1) above, because there can not be high casting temperature unless the melt has been overheated.

(3) Failure to skim the pouring pot properly, causing the occurrence of entrained dross in the casting.

(4) Collection of foreign matter—sand particles, gas, and the like—from the mold; this leads to surface sand holes and roughness, and is due to poor molds, wet molds, inadequate venting, or to pouring too fast, which causes erosion of the mold surface.

(5) Faulty pattern design, resulting in shrinkage holes and shrinkage cracks, and, consequently, unsoundness.

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[a] Pack, C., Die castings and their application to the war program; Bull. Am. Inst. Min. Eng., February, 1919, pp. 239–248.

[b] Rosenhain, W., An introduction to physical metallurgy, 2d ed., 1917, p. 294.

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As a casting is a final product whose defects can not be corrected to any extent after it is made, the aim is to produce as perfect a casting as possible. Some patching, welding or soldering may be feasible for some castings, but it is much cheaper to make good castings in the first place. The final structure as well as the constitution of any casting depends largely upon the rate of cooling and the rate of solidification in the mold. The best structure is obtained by controlling the rate of cooling; ordinarily the most suitable rate, from the standpoint of the practical foundryman, is the most rapid rate that can be employed and not result in cracking or warping from the setting up of casting strains. The rate of both cooling and solidification can be most readily controlled by regulating the pouring temperature; the discreet use of chills is a matter of prime importance to the aluminum founder, because it is hardly possible to make many kinds of castings on a production scale without the use of chills. A high casting temperature is extremely undesirable; leaving out of consideration the many other difficulties introduced by high-pouring temperature, it reduces the rate of solidification in that the abundance of excess heat may exhaust the thermal capacity of the mold before freezing even commences. In aluminum-alloy castings, high pouring temperatures result in excessively coarse microstructure, segregation, and oxidation. Consequently the temperature at the moment of casting should be as low as is possible, but not so low that imperfect castings will result through lack of fluidity consistent with ready filling of the mold, thereby causing cold shuts. While it is important to maintain a low-pouring temperature for casting aluminum alloys, it is equally important to avoid overheating the metal in the furnace charges. Doubtless some advantage is gained when overheated melts are allowed to cool to the correct pouring temperature, and part of the danger of overheating is minimized by so doing. Nevertheless, for aluminum, overheating is very objectionable because of the rate of dissolution of iron from cast-iron melting pots and of the reduction of silica from clay crucibles, as well as absorption of gases from the local atmosphere. For molten metals, the absorption of gases increases with rising temperature,[a] this being possibly due to the fact that metals form loose compounds with hydrogen and nitrogen. The absorbed gases are often held by the metal until solidification starts, when they are liberated and cause unsoundness. Hence, an overheated melt would contain more absorbed gases than one not overheated, and it would be expected that castings poured from the former would be more unsound than those poured from the latter.

In pouring a casting having angles and corners, the metal in these places is the last to solidify, hence in addition to shrinkage cracks

[a] Rosenhain, W., An introduction to physical metallurgy, 2d ed., 1917, p. 289.

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forming therein, there is a tendency for gases and other impurities to be forced into them, causing local unsoundness. In the solidification of a eutectiferous alloy, like No. 12 alloy, the later solidification of the eutectic tends to aggravate many of the effects due to unequal cooling and contraction, so that all the defects may be more prominent in a eutectiferous alloy than in a substantially pure metal or in a solid solution.

With these fundamental ideas at hand, consideration may be given to the general subject of gases in aluminum and aluminum alloys, so far as the available literature can furnish information.

GASES IN ALUMINUM.

As blowholes are intimately associated with gases, a profitable inquiry might extend in the direction of ascertaining the kind and amount of gases present in aluminum and aluminum alloys. The statement has been made that blowholes, sponginess, and porosity are caused by gases, dissolved in the molten metal, which are liberated on final freezing. Liquids, in general, dissolve less gas with increasing temperatures, but evidently molten metals depart from this law and dissolve more gas with rising temperatures.[a] Hence, the higher any metal or alloy is heated prior to casting, the more gas will be dissolved. According to the available information, the solubility of gases in liquid metals does not appear to obey Henry's law. Desch[b] states that such solutions readily remain supersaturated and therefore an overheated melt will usually contain more gas at the moment of pouring than a melt which has been merely heated to the correct pouring temperature. Evidently the porosity resulting from overheating may be largely overcome by remelting and pouring at the proper temperature. Also, practical experience and the results of tests made in connection with the present investigation have shown that cooling an overheated melt to the correct pouring temperature will aid in minimizing the undesirable effects of overheating.

From the foundry standpoint, two kinds of gas are recognized—namely, that evolved from the metal on freezing, and that liberated from the mold and core on pouring. Blowholes which are not the result of liberation of gas from the metal or mold or core are simply entrapped bubbles of air carried into the metal on pouring and held there. Irrespective of their causes, blowholes may often be deep-seated and may not be detected even after machining; but detected or unde-

[a] Sieverts, A., and Krumbhaar, W., Über die Löslichkeit von Gasen in Matellen und Legierungen [On the solubility of gases in metals and alloys], Ber. Deut. Chem. Gesell., Jahrg. 43, 1910, pp. 893–900.

[b] Desch, C. H., Some common defects occurring in alloys: Jour. Inst. Metals, vol. 4, 1910, pp. 235–246.

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tected, they constitute a source of weakness in the finished casting and are therefore to be regarded as defects.

Not much work has so far been done on gases in aluminum. Guichard and Jourdain[a] have examined samples of aluminum, from army utensils, containing appreciable amounts of copper—2.0 to 3.0 per cent copper. They found that the total quantity of gases evolved under the influence of heat in vacuum, under the same conditions, increased with the amount of alteration of the aluminum; the sound samples gave off relatively little gas, while the unsound samples evolved much gas. In sound samples, that is, unaltered by excessive corrosion and oxidation, an average of 0.25 c. c. of gas per 10 grams of metal was evolved; the gas contained roughly 62.0 per cent hydrogen, 10.0 per cent methane, 10.0 per cent carbon monoxide, 10.0 per cent carbon dioxide, and 8.0 per cent nitrogen. In the altered samples the hydrogen content was lower and carbon dioxide was the predominating gas; samples evolved gas containing up to 66.0 per cent carbon dioxide presumed to arise from the absorption of carbon dioxide by the surface alumina. The samples were heated to 550° C. Dumas[b] states that practically pure hydrogen may be evolved from aluminum, 80 c. c. being yielded from 200 grains of aluminum for a particular sample. Details of the experiments are not given. Guillemin and Delachanal[c] have obtained numerous results for copper alloys, and Carpenter and Elam[d] have analyzed the gases evolved from zinc bronze. For metals in general, the main principles have been set forth by Sieverts[e] and his collaborators.

No gas analyses were made in connection with the present investigation. As regards the general statement that gases are progressively more soluble in liquid metals with increasing temperatures, seemingly the reverse would be true; that is to say, when a liquid metal at high temperature is allowed to cool, gas will be evolved progressively. For the sake of discussion a few postulations may be made.

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[a] Guichard, M., and Jourdain, P. R., Sur les gaz de l'aluminum [Gases in aluminum]: Compt. rend., t. 155, 1912, pp. 160–163.

[b] Dumas, M., Sur les gaz retenus par occlusion dans l'aluminum et le magnésium [Gases retained by occlusion in aluminum and magnesium]; Compt. rend., t. 90, 1880, pp. 1027–1029.

[c] Guillemin, G. and Delachanal, B., Recherche sur les gas occlus contenus dans les alliazes de cuivre [Researches on the gases occluded in copper alloys]; Compt. rend., t. 151, 1910, pp. 881–883.

[d] Carpenter, H. C. Hand Elam, C. F., An investigation on unsound castings of admirality bronze (88 : 10 : 2); its cause and the remedy: Jour. Inst. Metals, vol. 19, 1918, pp. 155–175.

[e] Sieverts, A., and Krumbhaar, W., Über die Löslichkeit von Gasen in Metallen und Legierungen [On the solubility of gases in metals and alloys]: Ber. Deut. Chem. Gesell. Jahrg. 43, 1910, pp. 893–900. Sieverts, A., Über Lösungen von Gasen in Metallen [On the solubility of gases in metals]; Ztschr. Elektrochem., Bd. 16, 1910, pp. 707–712, and discussion, pp. 712–713; Die Löslichkeit von Wasserstoff in Kupfer, Eisen, and Nickel [Solubility of hydrogen in copper, iron, and nickel]; Ztschr. phys. Chem., Bd. 77, 1911, pp. 591 et seq.

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If a molten metal evolves gas on cooling, then holding a melt until it has cooled to a relatively low temperature should aid in getting rid of excess gases dissolved on overheating and permit the production of sounder castings than could be obtained by pouring at a high temperature. If, however, all the gas dissolved on heating to a high temperature is retained until the moment of final freezing and then evolved either in whole or in part, cooling to a low temperature before pouring can have no effect. The former view seems the more logical. Gas given off while the metal is molten escapes and apparently can do no harm, but that set free when the metal is solidifying is unable to escape owing to the viscosity of the metal, and blowholes result.

The available information as to the solubility of gases in aluminum is contradictory. Sieverts[a] states that aluminum dissolves neither hydrogen nor nitrogen but that at temperatures above 800° C. the latter reacts with the metal to form a nitride. This, so far as solubility goes, does not agree with the work of Dumas and that of Guichard and Jourdain. On the other hand, Brislee[b] mentions the occlusion of gases by aluminum, and says that he has found considerable nitrogen in remelted aluminum, particularly when the temperature was permitted to rise excessively above the melting point.

From a broad view of all these remarks, it follows that the properties of aluminum and its light alloys are markedly affected by gases, whether dissolved or held in loose chemical union. As the solubility of gases, both in solid and liquid metals, increases with the temperature, the effects of gases in aluminum are prone to be more pronounced the higher the metal is heated in contact with a gas. This is a general statement and should not broadly be applied to all gases. Hence, when melting aluminum alloys for casting, in an oxidizing atmosphere at least, the temperature should be kept as low as is compatible with good practice and still permit the melt to be transferred from the furnace to the molds.

SOLIDIFICATION OF LIQUID METALS.

A consideration of the solidification of liquid metals is of more than passing interest in the study of blowholes, and the main facts are here briefly outlined. The general subject of solidification from the liquid state has been thoroughly debated by Desch[c] and others. Substantially pure cast metals in the solid state normally consist of a number of allotriomorphic grains cemented together by thin films of the amorphous phase of the particular metal. Liquid metals are

[a] Sieverts, A., Über Lösungen von Gasen in Metallen [On the solubility of gases in metals] : Ztschr. Elektrochem., Bd. 16, 1910, pp. 707–712.

[b] Brislee, F. J., A redetermination of the density and coefficient of linear expansion of aluminum : Trans. Faraday Soc., vol. 7, 1912, pp. 221–227, and discussion, p. 228.

[c] Desch, C. H., The solidification of metals from the liquid state : Jour. Inst. Metals vol. 11, 1914, pp. 57–118.

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held to be totally amorphous. When the temperature of a liquid metal is lowered to the freezing point, crystallization commences from various nuclei, and the grain size of any frozen metal is dependent upon the rate of cooling during solidification. Metals of high freezing point, for example platinum, usually have a fine grain, whereas aluminum, having a fairly low freezing point, has a relatively coarse grain. The constitution and microstructure of any given alloy depends upon the rate of cooling and primarily upon the rate of solidification. In castings, control of the rate of solidification is important; particularly in the aluminum alloys because they are not, ordinarily, susceptible to heat treatment.

In foundry practice attempts are made to regulate the rate of solidification of castings by the use of suitable chills, and in many instances chills are necessary. In general, however, the best rate of solidification is simply the most rapid rate that can be used without causing warping or cracking. Chill castings, other things being equal, have a finer microstructure than sand castings; this is so because the chill mold rapidly conducts the heat away and consequently a rapid rate of solidification is obtained. As a sand mold is as poor conductor of heat, the metal remains hot for a relatively longer time. The rate of solidification of castings is also affected by the casting temperature, being slow for high casting temperatures; accordingly, castings should be poured at as low a temperature as possible.

When a metal passes from the liquid to the solid state the change is usually accompanied by a change in volume. Generally speaking, the commercial light aluminum alloys contract on solidification, and the amount of shrinkage for No. 12 alloy is taken as 1.30 per cent or 0.156 inch per foot. Desch[a] states that the percentage of volume increase on melting aluminum is 4.80 per cent. The change of volume on solidification of metals was found by Toepler to be a periodic function of their atomic weights. Turner suggested that aluminum expands on solidification, but the seeming expansion found by him is attributed by Chamberlain[b] to the influence of dissolved gases.

ANALOGY WITH STEEL.

The problem of making sound ingots and castings of steel has been the subject of much inquiry, and methods for the prevention of blowholes have been minutely studied in this connection. Most metallurgists have associated blowholes in steel ingots and castings with iron oxides[c] and to a less extent with oxygen itself, and the

[a] Desch, C. H., work cited, p. 96.

[b] Chamberlain, J. H., A study of the volume changes in alloys: Jour. Inst. Metals, vol. 10, 1913, pp. 193–234.

[c] Boylston, H. M., Investigations of the relative merits of various agents for the deoxidation of steel, Carnegie Schol. Mems. Iron and Steel Inst., vol. 7, 1916, pp. 102–171.

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substances that have been used for the prevention of blowholes and unsoundness are usually referred to as deoxidizers. These so-called deoxidizers in some instances might more properly be termed solidifiers, purifiers, or degasifiers, and lately the attempt has been made to recognize ferrotitanium and ferrocarbon-titanium as denitrogenizers. However, the essential fact to be recognized in the immediate discussion is that all the substances used for the deoxidation of steel—namely, silicon, titanium, manganese, aluminum, etc.—have a strong affinity for oxygen. Most steel metallurgists, therefore, associate oxygen with the presence of blowholes.

Alleman and Darlington[a] have summed up in an able manner the available information regarding occluded gases in iron and steel. The results of the investigations on the causes and prevention of blowholes in steel castings show that both iron oxides, oxygen, and other gases are important factors connected with the formation of blowholes; as to prevention of these defects, the use of deoxidizers for the removal of iron oxides and of various substances for increasing the holding power of the metal for gases have been employed successfully. With particular reference to gases in metals, some people have wanted to liberate the gas, others have desired to keep it in. So far as steel is concerned, no attempt is made to remove gases, but they are held in. Raw blown steel has been found to contain less gas than sound steel, and in both steels the gases were similar as to composition. In steel the holding power of the metal for gases is increased by additions of silicon and aluminum, which increase the solubility of hydrogen, nitrogen, and carbon monoxide. Baker[b] has shown that in a comparison of cast crucible steel as such and with the addition of aluminum, the latter evolved twice the volume of total gases obtained from the former on heating at 1000° C. for 110 hours.

In order to study systematically the effect of added elements on the soundness of aluminum-alloy castings, the literature in the same connection for steel will be found valuable. No information of practical value has yet been supplied for aluminum-alloy castings, and the entire subject is an open question.

EFFECT OF CASTING TEMPERATURE.

The temperature at which any alloy or metal is cast is a cogent factor in influencing the qualities of the resultant casting. In aluminum foundry practice, it is axiomatic that the pouring temperature should be as low as is compatible with the alloy filling the mold.

[a] Alleman, G., and Darlington, C. J., Occluded gases in ferrous alloys, Jour. Franklin Inst., vol. 185, 1918, pp. 161–198, 333–357, 461–480.

[b] Baker, T., Gases occluded in steel. Carnegie Schol. Mems. Iron and Steel Inst., vol. 1, 1909, pp. 219–229.

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Hence, aluminum founders strive for low pouring temperatures, and the introduction of suitable pyrometers has resulted in noteworthy improvements as regards correct casting temperatures. However, it does not follow that all aluminum-alloy castings are poured at the correct temperature, whatever that may be. In this connection, the following incident may be of interest as an example of the ill-advised use of pyrometers in the hands of some melters.

On a certain casting job, the pouring temperature was to be 1450° F. In watching the practice of temperature control and casting the writer observed that the melter would place the pyrometer in the pots on their way from the melting furnaces to the molds, hold the pyrometer in a given pot until the indicator showed 1450° F., and then pull it out, presumably so that the reading would not go any higher. Having so taken the temperature, orders would be given to pour. The writer, as a matter of interest, took the temperature of one pot and found it to be approximately 1700° F.; some of the other pots may have been even hotter. The foregoing is cited to indicate that the mere use of a pyrometer does not mean that correct pouring temperature will necessarily follow.

The actual pouring temperature to be employed in the production of aluminum-alloy sand castings varies with the melting point of the alloy and the design of the casting. Any foundryman knows that no definite pouring temperature can be assigned for general aluminum foundry practice; it would be well nigh impossible to set down a casting temperature to cover the range of every design of casting. However, reliable data on pouring temperatures would no doubt be welcomed by practical foundries. Design is a factor that powerfully influences casting temperature, because it is of first importance to insure that the melt is hot enough to fill the mold; a thin casting will be poured hotter than a thick one, and a complicated casting with thin webs and thick sections will be necessarily poured hotter than a simple casting. It should, of course, be borne in mind when discussing the effects of different factors independently, that various other factors also should be considered. Thus, in considering the effect of casting temperature on soundness, it should be remembered that many other causes may contribute to unsoundness, such as overheat-poor design, inadequate venting, etc. However, in discussing any any given variable, the contributary variables will be disregarded for the moment. This serves to simplify the discussion, and in the final summation all the variables can be considered in relation to each other and their combined and independent effects ascertained with some exactitude. Not only do many variables influence the soundness of aluminum-alloy castings, but these variables influence each other,

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so that the whole problem becomes exceedingly complicated. For example, high pouring temperature is conducive to blowholes, porosity, and unsoundness, and at the same time the design of the casting—that is, its weight, change of size of neighboring sections, contour, etc.—has a marked influence on the possible pouring temperature. It would be obviously incorrect and no doubt impossible to cast a crankcase for a 12-cylinder motor and a 0.25-pound housing for a vacuum sweeper at the same temperature. A discussion of the effect of variables on each other could be extended almost ad infinitum and would doubtless serve rather to dull the conceptions than sharpen them.

As has already been stated, the temperature at which any metal is cast is an important factor in influencing the soundness and strength of the resultant product. This has been shown, as regards strength, for aluminum-alloys by Gillett[a]; as regards soundness, for zinc bronze (88:10:2), by Carpenter and Elam[b]; and as regards the mechanical properties, for zinc bronze, by Karr and Rawdon.[c]

These writers and others have come to the conclusion that the casting temperature is of prime importance. The casting temperature affects the rate of cooling and consequently the microstructure and grain size, as well as the presence or absence of blowholes, porosity, and unsoundness, and occluded foreign material (oxides). For aluminum alloys Gillett has thoroughly demonstrated the importance of pouring temperature as a governing factor of the strength, but so far as is now known nothing is on record regarding the influence of this factor on soundness.

The experiments of Carpenter and Elam have shown that unsoundness in zinc bronze may result from pouring at too low or at too high a temperature, and these writers even go so far as to allege that the production of sound castings in zinc bronze is a problem of temperature control and nothing else. This is certainly a pretty broad statement when viewed by practical foundrymen, because it is well known that there are other contributory causes to unsoundness. For example, with ordinary No. 12 alloy (92:8 aluminum-copper), under otherwise identical conditions, a casting poured from metal which had been highly overheated for a long time would certainly be much more unsound than one poured from metal which had not been overheated, both being poured at the same temperature. This has been definitely demonstrated in the present tests as shown under

[a] Gillett, H. W., Influence of pouring temperature on aluminum alloys: Eighth Internat. Cong. App. Chem., vol. 2, 1912, pp. 105–112.

[b] Carpenter, H. C. H., and Elam, C. F., An investigation on unsound castings of admiralty bronze (88 : 10 : 2) ; its cause and the remedy: Jour. Inst. Metals, vol. 19, 1918, pp. 155–175, and discussion, pp. 176–220.

[c] Karr, C. P., and Rawdon, H. S., Standard test specimens of zinc bronze: Bureau of Standards Technologic Paper 59, 1916, 67 pp.

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"Description of Experiments" (pp. 24–30). In a discussion of Carpenter and Elam's tests, Dr. Longmuir[a] has pointed out that unsoundness in zinc bronze due to varying casting temperature is of secondary importance to that of the effect on other properties, for example, tensile strength. This observation probably accords with the known facts. Nevertheless, the general subject of unsoundness in nonferrous alloys, and particularly in aluminum alloys, is in a badly muddled condition; the presumed overwhelming argument for lightness—that is, low specific gravity—in these latter alloys, seems to have destroyed both the founders' and the engineers' sense of proportion. What is actually wanted are light, strong, and sound alloys; whether these are produced or not is another matter.

The effect of pouring temperature on blowholes, porosity, and general unsoundness is substantially this: The higher the temperature at the moment of casting, the more unsound is a casting liable to be, other things being equal. The fact, however, that pouring temperature is so important has been made the basis of much fallacious reasoning with regard to the quality of castings, for if the effects of molding, design, method of melting, and other factors, are disregarded, then all the available data are not properly marshaled and deductions are liable to be in error.

EFFECT OF THE METHOD OF MELTING.

Alloys of aluminum are melted in a variety of appliances, and there appears to be no well standardized mode. That the method of melting has a profound influence on the qualities of the resultant castings may be briefly indicated here. Aluminum alloys are melted in cast-iron pots, clay crucibles, and acid-lined open-flame furnaces: for fuel, oil, natural gas, artificial illuminating gas, producer gas, and coal have been used. Both the fuel and the containing vessel affect the quality of the metal. As regards the containing vessel, the tendency of substances in contact with each other is to establish a state of chemical equilibrium, and chemical interactions resulting from this tendency go on rapidly at more elevated temperatures. The dissolution of iron from cast-iron melting pots and the reduction of silica from clay crucibles or from fire brick in open-flame furnaces by molten aluminum alloys is a matter of common knowledge. High iron content is undesirable in aluminum-casting alloys, from the melter's standpoint, because the presence of more than 2 per cent iron appears to render melts of No. 12 alloy pasty and viscous at the normal pouring temperature.

[a] Longmuir, P., Discussion of article by H. C. H. Carpenter and C. F. Elam on "An investigation of unsound castings of admiralty bronze (88:10:2), its cause and the remedy": Jour. Inst. Metals, vol. 19, 1918, p. 195.

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In addition to being in intimate contact with the walls of the containing vessel, molten aluminum alloys will be in contact, more or less, with the furnace atmosphere; in open-flame melting the melt will be in direct contact with the flames and the products of combustion, but in crucible and iron-pot melting, this danger is somewhat minimized. In open-pot or crucible melting there is danger of contaminating the melt by allowing foreign matter to fall into the metal. Laxity in charging scrap in any method of melting may permit core sand, nails, wood, etc., to be charged. In an oxidizing atmosphere there will be ample opportunity for aluminum oxide to be formed, and this will influence the soundness of the castings. Desch[a] states that the remelting of alloys of aluminum and copper is usually necessary, in large-scale practice, for the purpose of eliminating the tough pellicle of aluminum oxide that is formed by oxidation during melting. The oxide, by remaining suspended in the liquid metal, prevents complete adhesion of the crystals and in this way reduces the strength and ductility of the alloy. Desch remelted a 90:10 copper-aluminum alloy three times and found no improvement in three successive casts. However, he claims that it is readily possible that minute films of aluminum oxide, insufficient to produce any weakening effect, might suffice to check the growth of crystals, and such films would be eliminated on remelting. He then qualifies this remark by stating that further experiments are necessary to decide whether such films are actually present.

The recent work of Rhodin[b] would go to show that aluminum oxide, calculated as Al_2O_3, is a normal constituent of all aluminum and aluminum alloys. Hence, it would be plausible to assume that a profitable line of attack would be melting in a reducing or neutral atmosphere in order to prevent oxidation. Open-flame melting under oxidizing conditions should normally be expected to be conducive to unsoundness in aluminum-alloy castings; there is more opportunity for oxidation and absorption of gases when melting in this way than when melting in crucibles or iron pots. Electric-furnace melting of aluminum is a rather recent accomplishment, and figures as to performance are not now available.

EFFECT OF THE RATE OF MELTING.

The rate of melting is closely connected with the method of melting; in fact, it would not be possible adequately to consider either without the other. The rate may vary between two extremes;

[a] Desch, C. H., The solidification of metals from the liquid state; Jour., Inst. Metals, vol. 11, 1914, p. 83.

[b] Rhodin, J. G. A., Contributions to the chemistry of aluminum and aluminum alloys; Trans. Faraday Soc., vol. 14, 1919, pp. 134–149.

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namely, the shortest time possible to melt a heat as contrasted with a considerably longer time. The amount of dissolved gas is a function of the temperature and, to a less extent, of the time of melting, not to omit mentioning the nature of the furnace atmosphere. For convenience and simplicity in considering rates of melting, from the standpoint of the practical foundryman, it is best to conceive of (1) a rapid rate of melting, and (2) a slow rate. In either instance, the rate will be affected by the temperature and by the size of the pieces melted. Other things being the same, it will take a longer time to liquefy a 1.0-foot cube of metal than a 1.0-inch cube. The reason is self-evident—namely, the time factor involved in bringing a larger mass to the melting point. This can be shown mathematically.

If the pieces of metal charged are small they can be melted more rapidly than large pieces. Also, the higher the temperature the more quickly will the charge melt down. A rapid rate of melting will be induced by charging small pieces and by employing a high temperature, while under reverse conditions a slow rate will obtain. High temperatures will permit increased solubility of gases, whereas low temperatures will inconveniently slow down production. From these brief considerations it would appear that the best rate of melting would be the most rapid rate that can conveniently be employed. The ill effects of gas solubility at high temperatures can be minimized by melting in covered pots or crucibles as contrasted with open-flame furnaces, and the rate may be increased for a given temperature by charging small ingots, rich alloy (50: 50 copper-aluminum, as regards light aluminum-copper alloys), and small pieces of scrap. The extreme of charging dust and exceedingly fine pieces of scrap can not be attained, because fine particles of aluminum coalesce with difficulty.

EFFECT OF THE METHOD OF MOLDING.

The effect of the method of molding on blowholes, porosity, and unsoundness may be conveniently presented by discussing the mold and cores in their relations to gases. It has been said that in casting practice blowholes can arise from gas derived from two sources—that evolved from the metal, and that set free by the mold. The inherent requirements of a mold are these: The mold must be strong enough to resist the washing effect of the hot metal stream; it must permit the easy escape of gases from the metal and from itself; and it must impart to the casting the desired shape and contour. No molten metal can remain in an impervious mold[a] because the gases evolved must find an outlet and would escape by throwing the metal through any possible opening, causing a "kick-back" through a runner or ejection through a riser. The gases evolved on pouring liquid

[a] McWilliam, A., and Longmuir, P., General foundry practice, 2d ed., 1912, p. 107.

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metal into a sand mold must be drawn through the sand, and it is necessary usually to augment the porosity of the sand by venting. The requirements demanded in a core are the same practically as those necessary in a mold, but conditions surrounding the core are intensified. The core is often entirely inclosed by liquid metal and consequently more difficulty obtains in providing a ready outlet for gases. If cores are capable of generating gases at the casting temperature—and this is usually the case—then if the gas is not removed through the core it must pass through the liquid metal. Gases generated from cores and molds when liquid metal is poured must be led away, as otherwise they will pass through the metal and give rise to porosity. Proper vents in cores and molds and correct ramming will provide the necessary outlet for gases. No comprehensive discussion of cores and molds in aluminum foundry practice will be included here; it is only necessary to point out that both cores and molds are factors in determining the soundness of castings.

EFFECT OF DESIGN OF CASTINGS.

The effect of the design of castings is important in connection with blowholes, porosity, and general unsoundness, but the foundryman can not do much, except within rather restricted limits, to control design. The difficulty lies in the designer's lack of appreciation of the difficulties in foundry practice, rather than in universally poor design. This condition can be ameliorated only by closer cooperation between designing engineers and practical foundrymen. The effect of design can be considered here in only a broad way, because of the large amount of detail inherent in the matter of designing castings, but if some general principles are elucidated they may be applied to any particular case.

Thick and thin sections in contiguity should be guarded against, as well as sharp reentrant angles. In the former instance the evils of contraction are largely augmented and a plane of weakness will exist at the dividing line of the thick and the thin sections. Rosenhain[a] has ably outlined the conditions that exist in the cooling of metal at a sharp reentrant angle, and it will be advisable to consider his view of the matter.

Figure 1 shows a diagram (after Rosenhain) of isothermals at a reentrant angle in a cooling casting. Close to the corner, the "heat conducted into the mold from one of the cooling surfaces which forms one branch of the angle must retard the cooling of the adjacent surface and vice versa; therefore the isothermals must curve inward toward such a corner. It follows that the metal actually at the corner will, for every successive layer, be the last to solidify. The

[a] Rosenhain, W., An introduction to physical metallurgy, 2d ed., 1917, pp. 291-293.

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metal at these points will, therefore, still be liquid when the remainder of the corresponding layers is already solid, and, as these already solid parts tend to contract as they cool, there is an obvious tendency to produce shrinkage cracks at these points where the metal is weakened, because hottest. There is also a tendency for gases and other impurities to be forced into these positions, and thus assist the other forces in bringing about local injury."

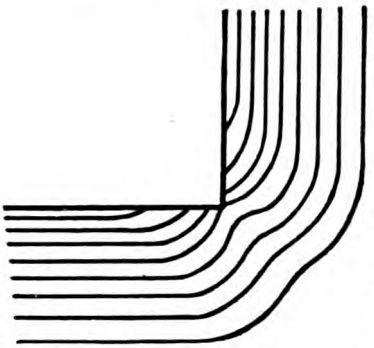

FIGURE 1.—Diagram of isothermals at a reentrant angle in a cooling casting (after Rosenhain).

The limitations imposed upon the foundryman by the nature of his business must be borne in mind by the designer. These limitations include the foundry layout, methods of melting and molding, capacity, quality of supervision, and means for metallurgical control. Metallurgical defects in any alloy may influence design, and design will be a prominent factor in deciding metallurgical practice. Alloys which are excessively hot short can not be used for complicated castings where thick and thin sections are in juxtaposition. If in any particular casting it is found impossible, from the standpoint of the designer, to eliminate thick and thin sections, an alloy having considerable elongation at elevated temperatures may be required, or the method of molding may have to be altered. In any event, there should be collaboration between designers and foundrymen; otherwise, high percentage of scrap from blowholes, porosity, unsoundness, shrinkage cracks, and warping will prevail.

EFFECT OF THE QUALITY OF INGOT.

Much uncertainty exists as to the influence of the quality of aluminum ingot on the soundness of the resultant castings. Some founders have the ill habit of blaming all foundry troubles on the "metal," when, in certain instances, it is sure that the fault laid with the foundry practice. A thorough discussion of ingot would be beyond the scope of the present work. The fact should not be forgotten, however, that the quality of the aluminum used for melting certainly does affect the quality of the resultant castings. Ingot which shows low physical values in the tensile test and which will not bend much in the bend test normally yields poor alloy castings; these may be excessively hot short, very porous, and unduly cracked. The indications are that brittle aluminum ingot is undesirable for sand casting, and is absolutely useless for die casting. Whereas 99 per cent ingot is regarded as superior to 98 to 99 per cent metal,

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the chemical analysis is not an absolute criterion as to quality, and must be supplemented by physical tests. The difficulty lies in the inadequacy of the present methods of analysis,[a] which do not tell the whole story. Inferior ingot can account for some of the unsoundness prevalent in sand castings.

As a matter of actual fact, the whole question is still unsettled, and convincing corroborative tests have been made only in isolated instances. It behooves all foundrymen in the light-alloy casting industry to look carefully into the quality of aluminum ingot for the purpose of correlating quality with the resultant castings. The influences of the various other factors, such as melting practice, method of molding, pouring temperature, and design, should not be overlooked.

SO-CALLED DEOXIDATION OF ALUMINUM.

Under the remarks applying to steel, reference has been made to the deoxidation and denitrogenation of steel as an aid in producing sound-steel castings. It is advisable in connection with soundness in aluminum-alloy castings to call attention to a number of beliefs now current. These are, briefly, the divergence of opinion as to whether aluminum oxide exists in aluminum, and the action of the so-called deoxidizers for the metal. It is considered proved, by the writer, that aluminum oxide, whether occluded Al_2O_3 or Al_3O_4 in solid solution in aluminum or both, is a normal constituent of all aluminum and aluminum-alloy castings produced by the present practices. It is also held by the writer that there now is known no commercial method for the deoxidation of aluminum. Various substances have been suggested at different times as deoxidizers, including magnesium, boron, phosphorus, phosphor-copper, etc., and various so-called "fluxes" have been introduced for the same purpose. The reminiscences of some foundrymen and the tales told by "flux experts" would almost lead one to believe that most of the sound castings are made through a system in which no consideration whatever is given to casting design, kind of alloy, methods of melting and molding, pouring temperatures, and technical control of foundry practice. By the introduction of mysterious fluxes, the character of which is carefully concealed and held "secret," all the inherent troubles incident to the manufacture of aluminum-alloy castings are totally eliminated—according to the reports. Metallurgists are well aware that this is utterly silly and unsound in principle, and yet a profitable business has been built up in so-called deoxidizers and fluxes for aluminum.

[a] Anderson, R. J., Metallography of aluminum inget; Chem. and Met. Eng., vol. 21 Sept. 1, 1919, pp. 229–234.

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Law,[a] a few years ago, remarked "it is true that one's sympathies would naturally be extended to the unfortunate metallurgist who was asked to determine the oxygen in an aluminum alloy." That condition has not yet been widely changed. In fact, all tests which have been made purporting to deoxidize aluminum have been practically useless because determinations of the oxygen or aluminum oxid contents of the samples have not been carried out. Typical of what has been written on the deoxidization of aluminum for the use of foundrymen is a paper[b] whose original premises were erroneous and whose measure of the deoxidizing effect of magnesium was the tensile test. It is impossible to take such tests seriously. In short, actual scientific information on the subject is not at hand.

DESCRIPTION OF EXPERIMENTS.

The most common alloy used in the United States for the production of light castings is that one known in the trade as No. 12 alloy—that is, 92 per cent aluminum and 8 per cent copper. This alloy, or others of a similar composition, is employed for a wide variety of castings, and aluminum founders are doubtless more familiar with it than with any other one. Hence, in the experimental tests made in connection with the present work it was considered advisable to use this alloy. The experimental work performed has already been discussed in another report.[c] In the tests about to be described, confirmatory evidence of already known facts has been obtained, and some new data have been made available. The effect of pouring temperature and length of time of melting period on soundness has been studied. The present work did not go into the influence of various furnace atmospheres on the soundness of castings, but that is a matter which merits consideration, and which seemingly has been given entirely too little attention.

In the tests made in connection with the present work, small heats of about 25 pounds each of the 92:8 aluminum-copper alloy were made up. The heats were charged as follows: The requisite amount of 50:50 aluminum-copper rich alloy was first melted down in a plumbago-clay crucible, using a gas-fired melting furnace: when the rich alloy had melted, enough virgin aluminum ingot, in the form of 3-pound six-notch bars, together with about 10 per cent of No. 12 gates and risers were added to make up the heat. Six sets of castings were poured, and the essential information is summarized in Table 1.

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[a] Law, E. F., The influence of oxygen on the properties of metals and alloys: Jour. Inst. Metals, vol. 8, 1912, pp. 222–230.

[b] Lane, H. M., Use of magnesium in deoxidizing aluminum alloys: Trans. American Brass Founders' Assoc., vol. 4, 1910, pp. 103–116.

[c] Anderson, R. J., Blowholes, porosity, and unsoundness in aluminum-alloy castings: The Foundry, vol. 47, 1919, pp. 579–584.

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TABLE 1.—*Data on six heats made on aluminum alloy to determine temperature effects.*

Heat.[a]	Treatment.	Pouring temperature, °C.	Remarks applying to appearance of castings.[b]
A.....	Charge heated to 650° C. and poured at once.	650	White, good, smooth appearance.
B.....	Charge heated rapidly to 860° C. and poured at once.	850	Tinted with oxidation stains; rough appearance; many surface holes.
C.....	Charge heated rapidly to 880° C.; removed from furnace and cooled to 630° C.	630	White, fair appearance; cold shut.
D.....	Charge heated to 650° C. and held in the furnace for one hour at 650–720° C.	640	White, fair appearance; cold shut not so marked as in C.
E.....	Charge heated rapidly to 900° C. and held in the furnace for one hour at 900–950° C.	950	Oxidation stains; bad looking casting, rough; many surface holes.
F.....	Charge heated rapidly to 900° C.; held in the furnace for one hour at 900–950° C.; removed from furnace and cooled to 700° C.	700	White, fairly good surface appearance.

[a] Duplicate runs of 25-pound charges were heated in a gas-fired furnace.
[b] Average chemical composition was copper 7.62 per cent, iron 0.39 per cent, silicon 0.26 per cent, and aluminum (by difference) 91.73 per cent.

The castings were simply thin shells as shown in Plate I, *C* (p. 8), the dimensions being roughly 7.625 by 6 by 4.125 inches and 0.125 inch thick. The cut-out portion, shown in the photograph, is simply a place where a section was removed for microscopy. Two kinds of castings were poured from the first six heats—(1) the thin shells, and (2) bars 0.75 inch square by 12 inches long. The shells are hereafter referred to as castings and the bars as bars for the sake of clearness in distinction. Castings of different thicknesses were thus poured for the purpose of ascertaining whether any exaggeration of defects might be traced to size of section under otherwise identical conditions. The castings and bars were poured in ordinary sand molds, properly rammed and vented; each casting was poured in a single mold and its companion bar in a separate mold. In the first six heats, the influence of pouring temperature and length of time of melting on soundness was observed. Duplicate runs, in which the data were essentially as already shown in Table 1, were also made for checking purposes. A composite sample of the first set of six castings and bars averaged 7.62 per cent copper, 0.39 per cent iron, 0.29 per cent silicon, and 91.73 per cent aluminum (by difference).

Before dealing with the second set of tests, summarized in Table 2, it may be well to elucidate the first set of tests.

Table 1 shows that heat A was kept at as low a temperature as possible, compatible with fairly rapid melting, and as soon as the charge was totally in solution, the castings and bars were poured. The total time in the furnace necessary for solution was approximately 30 minutes for all the heats, starting with a hot furnace and hot crucible. The shells poured from heat A were regarded as good castings, moderately sound, and of satisfactory surface appearance. Sand holes were few.

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In heat B, the charge was rapidly brought to 860° C., and the castings and bars were then poured. The total time in the furnace was about 40 minutes. The resultant castings from this heat were extremely poor; the surfaces were rough, with many sand holes, and the castings were dark colored.

In heat C, the charge was heated rapidly to 880° C., the total time in the furnace being about 40 minutes; the crucible was then removed and permitted to cool in the air to 630° C., at which temperature the castings and bars were poured. On account of the low pouring temperature, the shells were cold shut, but other than that their surface appearance was satisfactory; there were few sand holes.

Heats D, E, and F were held in the furnace for 1 hour after complete solution was effected; heat D was in the furnace 1 hour and 30 minutes, heat E 1 hour and 40 minutes, and heat F 1 hour and 45 minutes. This was done so as to obtain figures on the effect of the length of time of melting on soundness. Heat D was held in the furnace for an hour after solution was effected; the temperature was kept fairly low, and the castings and bars were finally poured at 640° C. The resultant shells were cold shut, but not so markedly as in heat C, poured at 630° C. The surface appearances of both bars and castings were considered satisfactory; there were only a few surface sand holes. Heat E, poured at 950° C., after being held in the furnace for an hour at 900° to 950° C., gave very poor castings; the surfaces were rough and had many sand holes, and the color was dark and dirty. Heat F, however, resulted in fairly good castings; this heat was poured at 700° C. after heating for an hour at 900° to 950° C.

Additional tests of the effect of the pouring temperature alone on unsoundness were made by making up 60.0-pound heats of the 92:8 aluminum-copper alloy, in the manner previously described, and pouring bars 1.50 inch square by 12.0 inches long at 50° C. intervals as shown in Table 2. Duplicate runs were made for the purpose of checking. In the tests summarized in Table 2, a charge of 60.0 pounds was heated rapidly to 975° to 1,000° C.; the crucible was then removed from the furnace, and bars were poured at 50° C. intervals from the same pot by allowing the melt to cool between pours. The range of pouring temperature, as indicated in Table 2, was from 950° to 650° C. The average composition of a composite sample of the 1.50-inch square bars was copper 7.55 per cent, iron 0.36 per cent, silicon 0.29 per cent, and aluminum 91.80 per cent, by difference. In connection with these tests, some interesting information on the contraction of the No. 12 alloy was furnished by examination of the frozen pouring gates, and this will be dealt with in a later paragraph.

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The resultant castings and bars from all the heats, referred to as A to M, inclusive, were examined for surface appearance and microscopically for general characteristics and unsoundness. Polished microsections of both castings and bars were examined microscopically, and machined surfaces were inspected for blowholes. All temperatures in these experiments were taken with a base-metal thermocouple of the pyod type.

TABLE 2.—*Results of heating alloy to 950° C. and pouring at 50° intervals.*

Heat.[a]	Pouring temperature °C.	Remarks applying to appearance of castings.[b]
G	950	Soundness, surface appearance, and color vary with the pouring temperature.
H	900	
I	850	
J	800	
K	750	
L	700	
M	650	

[a] Duplicate runs of 60 pound charges were heated in a gas-fired furnace to 975–1,000° C., the crucible was then removed from the furnaces and bars were poured at 50° C. intervals.
[b] Average chemical composition was copper 7.55 per cent, iron 0.36 per cent, silicon 0.29 per cent, and aluminum (by difference) 91.80 per cent.

METALLOGRAPHY OF UNSOUNDNESS.

The castings and bars poured in heats A to M, inclusive, were examined macroscopically and microscopically for blowholes, porosity, and general unsoundness. In examining castings for relative unsoundness, this defect can be judged most conveniently by simply inspecting polished or machined surfaces. Microscopic examination is not so useful. In the present experiments the bars cast from the various heats were machined smoothly by milling, and the surfaces were inspected for holes. Microsections from the bars and castings were also prepared and studied. As indicative of what a macrograph can show as regards relative soundness, reference may be made to Plate II, *A*, and Plate II, *B*. The former shows the surface appearance of a microsection cut from a 0.75-inch square bar cast from heat D; the latter is a similar macrograph from heat E. Heat D, it will be recalled, was poured at 640° C. and heat E at 950° C. Machined surfaces also show relative unsoundness and blowholes fairly satisfactorily. Macrographs of samples from heat G to M, inclusive, proved extremely instructive. Plate II, *C*, and Plate III, *A*, show the surface appearances of polished sections cut from samples taken from heats H and M, respectively. In general, the number of blowholes per unit area, in aluminum-alloy sand castings of the 92:8 type increases with increasing pouring temperature. Plate II, *C*, shows many large holes, while Plate III, *A*, shows a few small holes.

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The microsopic examination of sections cut from the various bars and castings served to throw some light on the question. Evidence of at least three kinds of unsoundness was obtained from the microscopic study, as follows: (1) That which is plainly intergranular and may be due to an actual forcing apart of the grains by gas attempting to escape or due to intergranular occluded foreign matter; (2) that due to liberation of gas which is entrapped at the moment of final freezing and can not escape, resulting in blowholes of varying size; (3) that which is the result of balled-up oxide occluded indiscriminately in rather large gobs in the frozen alloy. Typical micrographs showing various structures are presented in Plate III, *B*, Plate III, *C*, Plate IV, *A*, and Plate IV, *B*.

It may be noted in comparing the microstructures of the 0.75-inch bars and the 0.125-inch castings that in the former the grain size is much larger than in the latter. This is, of course, to be expected, as a thin casting is chilled much more rapidly by the sand than a thick one; a thick casting may even exhaust the thermal capacity of a sand mold before solidification, provided conditions are right. Intergranular occluded foreign matter, whether aluminum oxide or not, is shown by Plate III, *C*, while unsoundness due to (3) is illustrated by Plate IV, *B*. Plate III, *B*, and Plate IV, *A*, are typical micrographs showing the average structures of the 0.75-inch square bars and the 0.125-inch thick castings, respectively. In each of these two sections selected sound spots were taken for photography.

RADIOGRAPHY OF CASTINGS.

The proposal has been made by Davey[a] and others, and actually carried out in some instances, that X-ray photographs of castings would prove useful in determining the presence or absence of blowholes. In fact, Tonamy[b] has attempted to decide by radiographs whether or not castings are worth machining. As regards aluminum-alloy castings, some machine-shop scrap is the result of undue porosity and blowholes being found after a few cuts taken with a milling tool, for example in the machining of motor castings.

In connection with the present tests, it was thought that possibly an X-ray examination would be of assistance in locating the presence of internal blowholes, as well as general porosity and sponginess, without cutting the suspected samples and polishing as in metallography. Accordingly, some samples of the 92:8 aluminum-copper alloy were prepared and radiographed in the usual manner. Two different sets of samples were prepared—0.25-inch by 4.0-inch by

[a] Davey, W. P., Radiography of metals, Trans. Am. Inst. Min. Eng., vol. 53, 1916, pp. 150–160; Application of the coolidge tube to metallurgical research, Gen. Elec. Rev., vol. 18, 1915, pp. 134–136.

[b] Tonamy, C. H., Detection of internal blowholes in metal castings by means of X rays, Jour. Inst. Metals, vol. 14, 1915, pp. 200–203.

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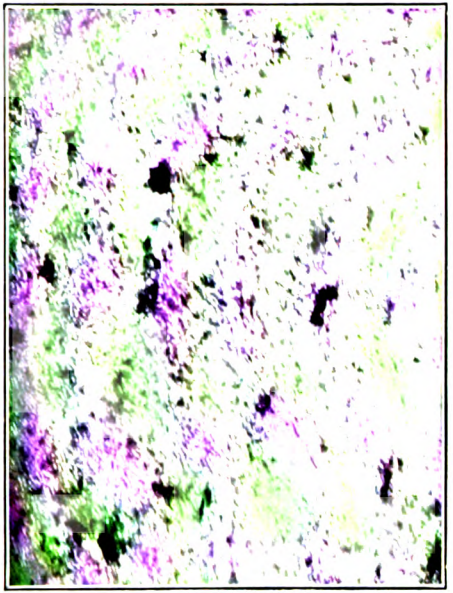
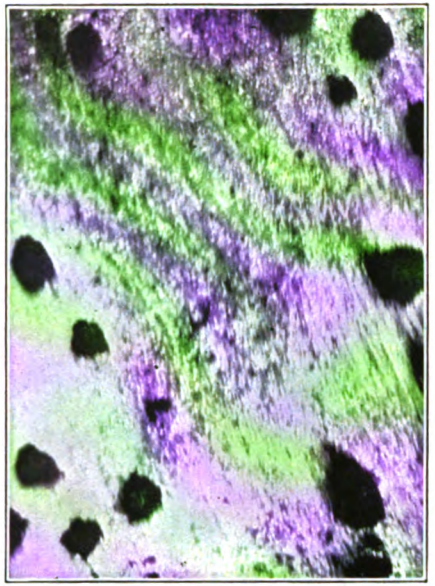
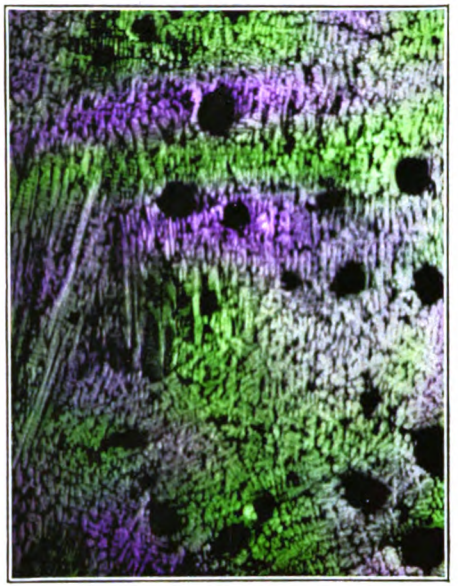


A. UNSOUNDNESS AND BLOWHOLES IN 92:8 ALUMINUM-COPPER ALLOY POURED AT 640° C.; LIGHTLY ETCHED WITH NaOH; VERTICAL ILLUMINATION. (X 7)



B. UNSOUNDNESS AND BLOWHOLES IN 92:8 ALUMINUM-COPPER ALLOY POURED AT 950° C.; LIGHTLY ETCHED WITH NaOH; VERTICAL ILLUMINATION. (X 7)



C. ALLOY FROM HEAT H, POURED AT 900° C.; DEEPLY ETCHED WITH NaOH; VERTICAL ILLUMINATION. (X 7)

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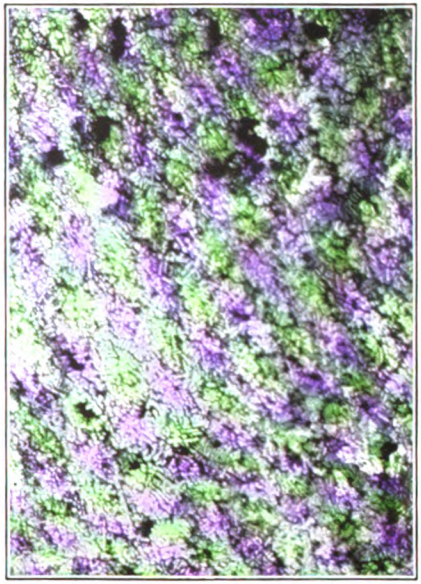
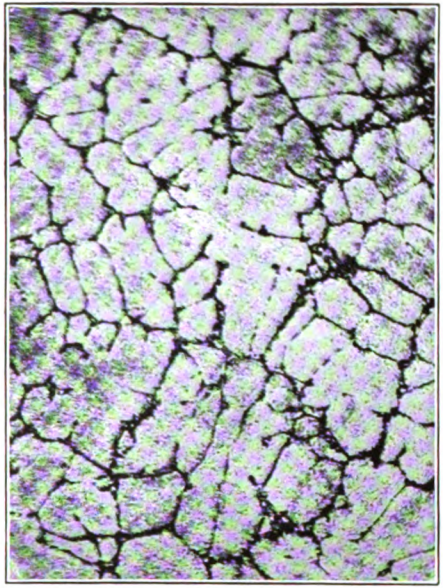
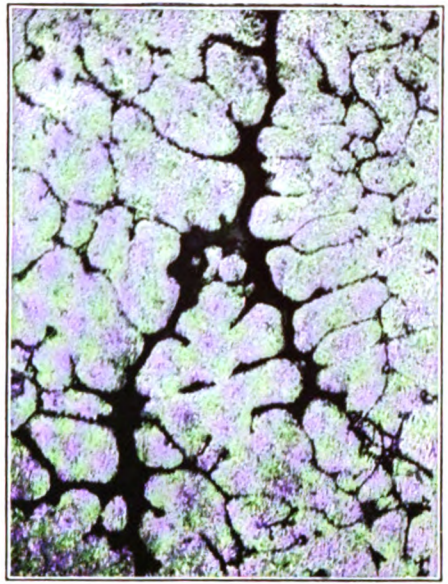


A. ALLOY FROM HEAT M, POURED AT 650° C.; DEEPLY ETCHED WITH NaOH; VERTICAL ILLUMINATION. (X 7)



B. ALLOY FROM HEAT A, POURED AT 650° C.; FROM THE BAR, SOUND PORTION; ETCHED WITH NaOH. (X 75)



C. ALLOY FROM HEAT B, POURED AT 850° C.; FROM THE BAR, INTERGRANULAR UNSOUNDNESS; ETCHED WITH NaOH. (X 75)

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6.0-inch plates, and 1.0-inch by 1.0-inch by 12.0-inch bars. In both plates and bars porous, unsound samples were made by casting at 950° C. in a damp mold, and fairly sound samples of each were made by casting correctly at a low temperature, i. e., 650° C. X-ray photographs of the porous and sound plates and bars were taken.

The conclusions drawn from the radiographs are that with the tube used it was impossible, in the castings radiographed, to determine whether the speckly effect in the radiographs resulted from the differential rate of passage of the rays through the solid solution matrix and the surrounding eutectic or to general porosity. Where large blowholes are present in samples obtained from various aluminum foundries, as for example in certain crank-case castings, it was possible to detect internal blowholes fairly readily. However, considerable doubt is entertained as to whether radiography as applied to aluminum-alloy castings for the purpose of detecting internal blowholes can serve any practical purpose. In order to determine whether a complicated casting would be worth machining would require a large number of radiographs at least, and it might be impossible to take radiographs which would furnish interpretable information. As a matter of fact, it will be found much more economical to make the original casting sound on the molding floor.

MISCELLANEOUS CONSIDERATIONS.

Although this report makes no attempt to deal with the subjects of cracks in castings, it may be said that the origin of cracks is often confused. Cracking in an aluminum-alloy casting is customarily regarded as resulting from direct fracture of the metal by reason of contraction in volume on passing from the liquid to the solid state. Considerable variation in size of contiguous sections augments the tendency to cracking. That some surface cracks are intimately associated with deep-seated internal blowholes has been shown by fracture studies. In a number of sections it was found that the surface cracks penetrated into an interior blowhole of rather large size, say 0.25-inch diameter, and that the blowhole caused the cracks. The examination of surface cracks in aircraft motor castings and inspection of polished microsections from the same castings indicate that blowholes may be associated with surface cracks and may even be the direct cause of them. A rather badly cracked crankcase, made of the 92:8 aluminum-copper alloy, may be cited in support of this view. Plate IV, *C*, shows the microstructure of a section cut from this particular casting from a portion which was badly cracked as to surface. In examining fractures of the same casting, internal blowholes (see point X, Plate IV, *D*), were found from which cracks led to the sur-

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face. This is an interesting matter, and, so far as the writer is aware, has not been discussed hitherto in the literature.

It might be inferred from what has gone before that the writer believes perfectly sound castings can be made at all times. No such inference should be drawn. Evidently, however, many castings are needlessly unsound. For certain castings, where neither strength, soundness, nor good surface appearance are desired, there will be no object in making strenuous efforts to guard carefully the quality of the product. A consideration of economic importance, however, may enter here; if the assumption is made that the use of unsound scrap can affect the quality of castings made therefrom, then it might, as regards conservation, be desirable to produce sound castings entirely. What may be regarded as permissible defects—that is, blowholes, porosity, unsoundness, cracks, and the like—varies so much with different castings that it is totally beyond the scope of this paper to deal with them. It is enough to say that permissible defects depend upon the casting made, the use for which it is destined, and the specifications under which it is manufactured.

The effect of pouring temperature on contraction of the 92:8 aluminum-copper alloy, as previously mentioned, is aptly illustrated by the photograph in Plate V. This shows the heads of the pouring gates of the series of bars cast at 50° C. interval, in heats G to M, inclusive, Table 2. The amount of contraction is a function of the pouring temperature, so far as the limitations of the experiments can show, but whether it is also, at the same time, connected with dissolved gases is not certain. It is a fact, however, that a casting poured at 950° C. contains more dissolved gases at the moment of pouring than one poured at 650° C.

Gate G in Plate V was poured at 950° C., gate M at 650° C., and the others at 50° C. intervals. Gate G actually expanded in the head, while the shrinkage of gate M is marked and apparently normal. Gradations in the amount of expansion and contraction are shown in the other gates depending upon the pouring temperature. Gate J, poured at 800° C., seemingly did not contract or expand much; gates G, H, and I expanded; gates K, L, and M contracted.

CONCLUSIONS.

Broad generalizations of value can not be drawn from the results of the experimental work, the experience of the various foundries, and the contradictory literature. In other words, it is impossible to compile a code of directions that a melter can follow faithfully and obtain 100 per cent sound castings all the time. This much, however, is fairly well settled: That it is possible to recognize the exist-

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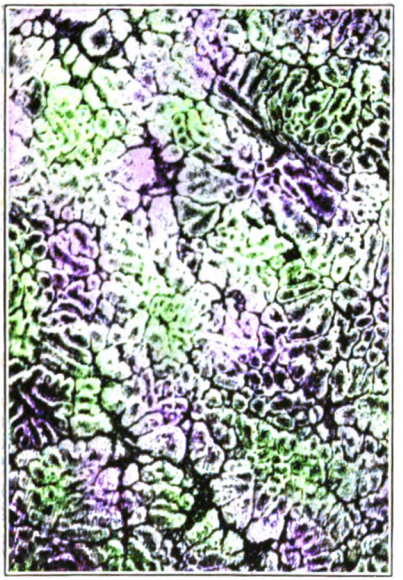
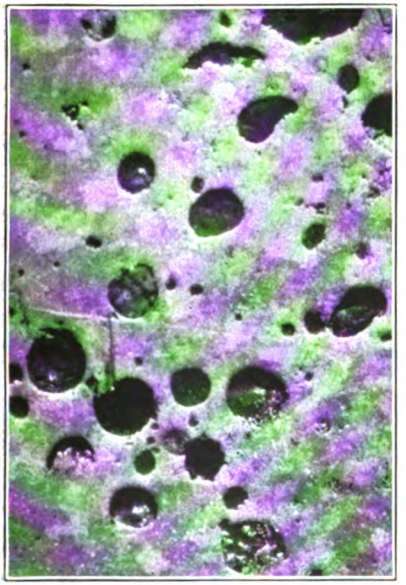
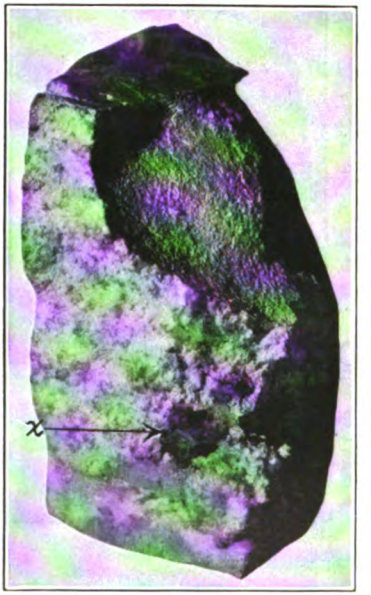


A. ALLOY FROM HEAT D, POURED AT 640° C.; FROM THE CASTING; ETCHED WITH NaOH. (X 75)

B. ALLOY FROM HEAT E, POURED AT 950° C.; FROM THE CASTING; ETCHED WITH NaOH. (X 75)



C. BLOWHOLES IN A SAMPLE TAKEN FROM A CRANK CASE. (X 5)



D. INTERNAL HOLE SHOWN ON FRACTURE IN A SAMPLE REMOVED FROM A CRANK CASE. (ACTUAL SIZE).

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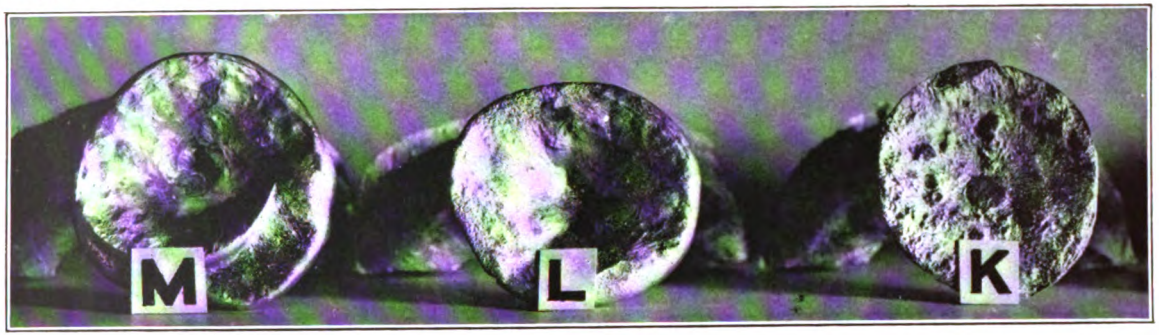

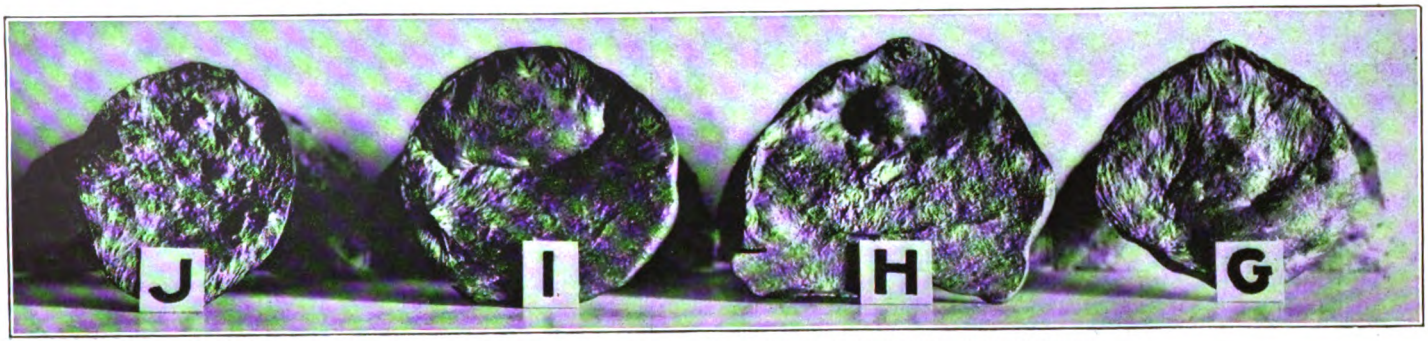

POURING GATES FROM HEATS G TO M IN THE CASTING EXPERIMENTS.

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ence of a large number of variables that may conduce to unsoundness and blowholes; that some of these variables patently are much more conducive to unsoundness than others; and that there are possibilities of developing methods for eliminating these defects. The main conclusions that can be drawn with confidence from actual observation in the experimental heats may be summarized as follows:

(1) The number of blowholes present is a function of the pouring temperature; the higher the pouring temperature the greater the number of blowholes and the more unsound is the casting.

(2) Unsoundness varies with the temperature to which the charge is heated; the higher the temperature in the furnace the more unsound the resultant castings are, irrespective of the pouring temperature.

(3) Unsoundness is a function of the length of time of melting; the longer any melt is held in the furnace the more unsound are the castings, irrespective of the temperature of heating and the pouring temperature.

It can be readily seen that the factors affecting the soundness of castings can influence one another either favorably or adversely. Thus, pouring an overheated melt at a lower temperature by allowing the charge to cool prior to pouring will aid in minimizing the deleterious effects of overheating. Castings poured at low temperatures are more sound than those poured at high temperatures, but heats held in the furnace for a long time at either high or low temperatures are more unsound than those held for a short time. The most aggravated cases of unsoundness will result from pouring a melt at a high temperature which has previously been excessively overheated and for a long time. There is nothing to lead to the belief that there is a minimum temperature below which it is not safe to go for fear of unsound castings resulting from too low pouring temperature.

The results of the experimental heats and also past foundry experience, together with the general information available, would lead to the conclusion that, with the methods of melting now in vogue, the heats should be kept at a low temperature in the furnace, melting should be as rapid as possible—that is, the charge should be poured as soon as it is melted—and the pouring temperature should be as low as is consistent with the metal filling the mold. These conditions can be attained only by close supervision of melting and pouring, together with a study of the appropriate correlation between the molding floor and the furnace room. It will be best to have the molding floor waiting for metal rather than have the furnace room waiting for molds. Close pyrometric control is also presupposed in actual foundry production.

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